Correlation between Chiral Fluctuations and the Topological Hall Effect

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Introduction

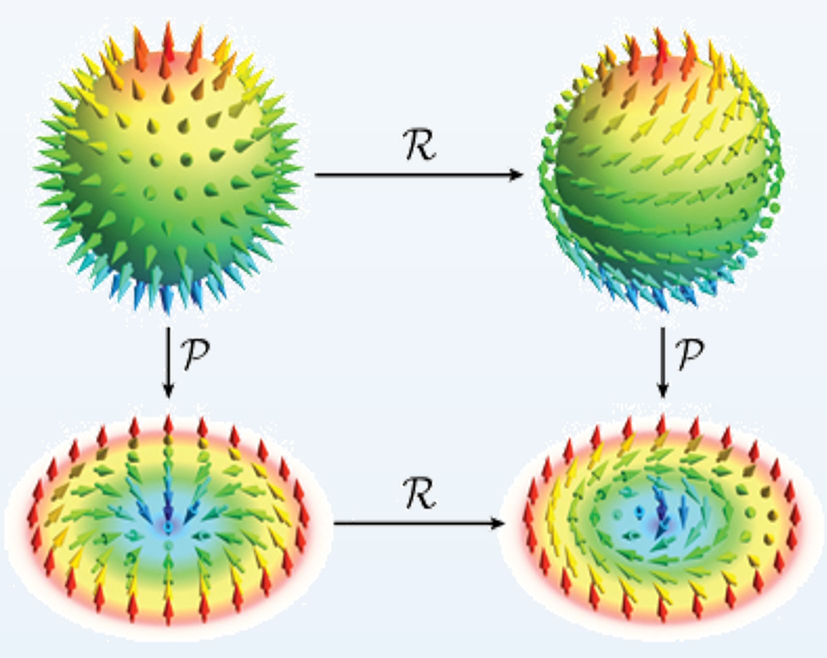


Figure 1: Skyrmions with various spin configurations [1].

- Magnetic skyrmion is a nanoscale vortex of spin texture.
- Skyrmion can be manipulated with electric current.
- Skyrmion is a topological spin texture that is robust against disorder.

Significant of Skyrmion

A robust nanoscale topological spin texture that can be manipulated by a small electric current make it a great candidate for next-generation memory devices.

The topological Hall effect (THE) is used as the exclusive signature of skyrmion's presence in a material. However, we show that thermal driven topology does show up in transport measurement. In this project, we aim to better understand the theory behind the topological Hall effect. **Understanding the mechanisms of the topological Hall effect is crucial for accurately identifying topological spin structures in materials.**

Objectives

- Simulate a 2-D chiral magnet at high temperature and moderate magnetic field.
- Model the conduction electrons with the tight-binding model.

$$H = -t\sum_{\langle ij\rangle} c_i^{+} c_j - J_H \sum_i c_i^{+} \boldsymbol{\sigma}\cdot \boldsymbol{S} c_i$$

- Calculate the Hall conductivity and longitudinal conductivity of the spin lattice using the Kubo formula [2].

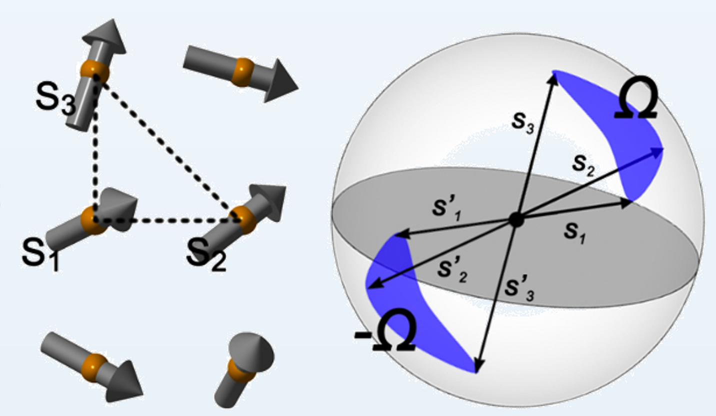
$$\sigma_{xy} = \frac{2\pi}{L^2}\sum_{m\neq n}\frac{f_n - f_m}{\eta^2 + (\varepsilon_m - \varepsilon_n)^2}\mathrm{Im}(\langle m|J_x|n\rangle\langle n|J_y|m\rangle)$$

- Study the correlation between transport results and thermal emergence topology.
- Study the strong and weak coupling regime, and the Hall resistivity dependence of the scattering time, $\tau = \eta^{-1}$.

Methodology

- Initialize a random spin lattice and simulate it with the Monte Carlo algorithm with the Hamiltonian: $H = \sum_{<ij>} -J\mathbf{S}_i\cdot\mathbf{S}_j + \mathbf{D}_{ij}\cdot(\mathbf{S}_i\times\mathbf{S}_j) - \sum_i \mathbf{H}\cdot\mathbf{S}_i$
- Simulate across the dotted line in Figure 2.
- Calculate the observables: scalar chirality, topological charge (TC), and transport data: $\sigma_{xy}, \sigma_{xx}, \rho_{xy}$.

TC: $Q = \frac{1}{4\pi}\sum_{i=1}\Omega_i$



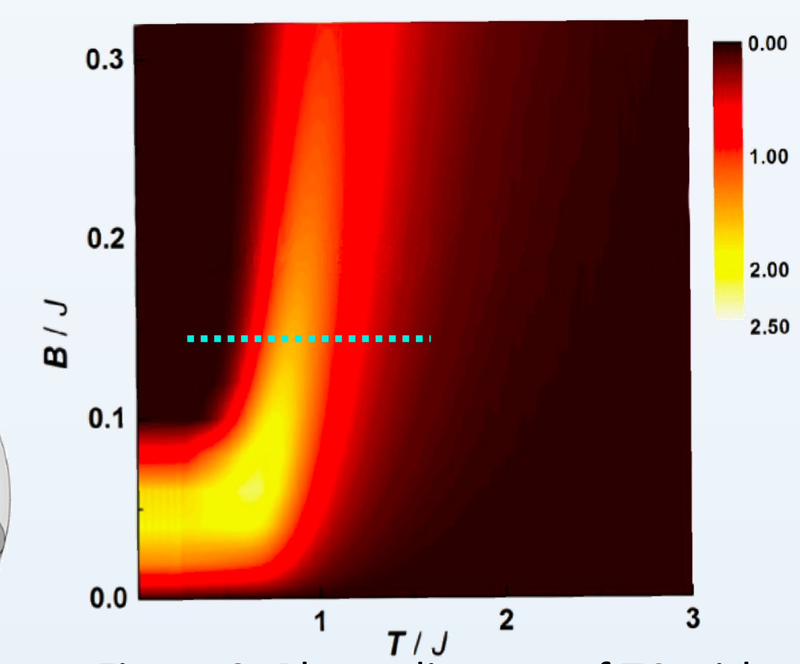


Figure 2: Phase diagram of TC with D = 0.3. The dotted line is the thermal fluctuation region [3].

- Vary J_H to obtain the strong (J_H >> t) and weak (J_H ~ t) coupling regime.

Results

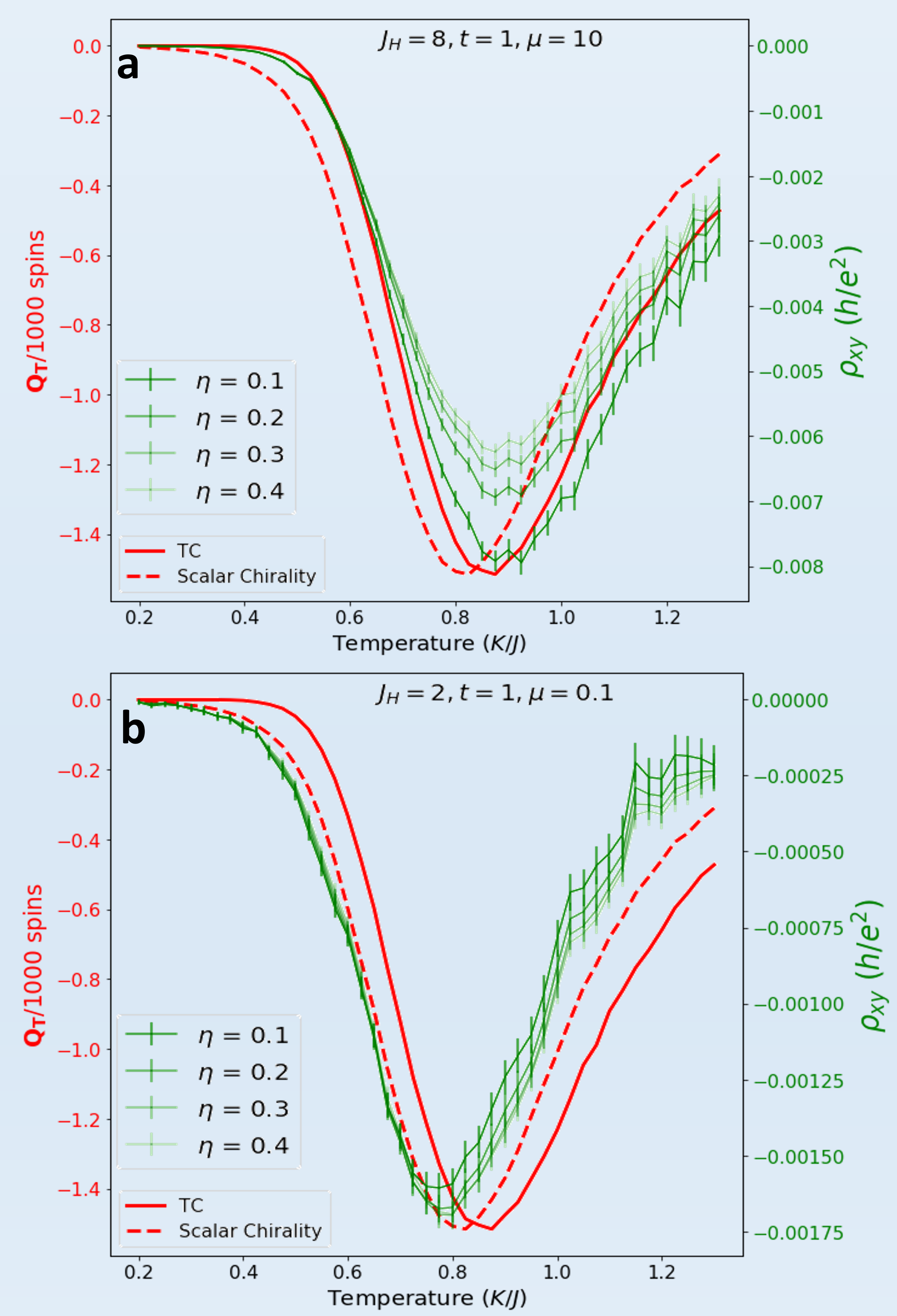


Figure 3: Topological charge (solid red), scalar chirality (dashed red), and Hall resistivity (green). 3a is strong coupling and 3b is weak coupling.

- Thermal emergence topology has transport signature.
- There is a crossover from weak to strong coupling regime. The topological Hall effect is controlled by TC and chirality.
- Correlation coefficients are above 0.95.
- Hall resistivity in the strong and weak coupling have different scattering time dependence. $\rho_{xy} \propto \tau^2$ for strong coupling, but ρ_{xy} increases for decreasing scattering time in the weak coupling regime.

Discussion

- The topological Hall effect can not be used to claim the presence of skyrmions.
- A recent experiment on the transition metal oxides shows a non-zero THE near the critical temperature. This is consistent with our results.

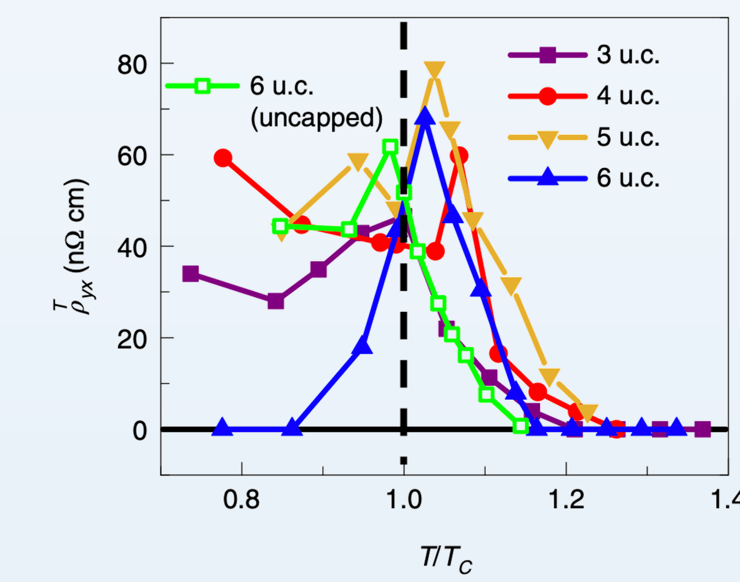


Figure 4: Topological Hall effect near the critical temperature in $SrRuO_3$. The THE is due to spin fluctuations [4].

- Topological charge is consistent with the strong coupling theory and chirality is consistent with the weak coupling theory.

Significant

- This work resolves our understanding of topological charge and scalar chirality at high temperature.
- Consistent with experimental results and can explain the origin of the topological Hall effect at high temperature.

Future Work

- More in-depth analysis on the scattering time.
- Investigate thermal emergence of topological charge in DM-free system.

Acknowledgement

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